

Rotational Ground Motions

ECI 284 Term Paper

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Introduction

The response of structures to ground motion has traditionally been done by looking at only the translational motions from earthquakes. However, to fully describe motion of a rigid body in the Cartesian system, three translational and three rotational values are needed (shown in Figure 1).

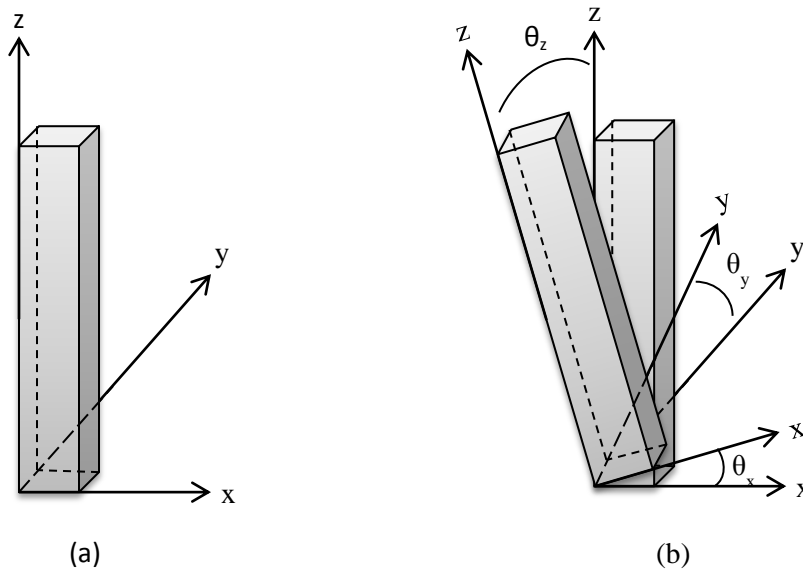


Figure 1: (a) Translational Only (b) Translations with Rotations

Richter (1958) stated that “Theory indicates, and observation confirms, that such rotations are negligible”. This was reaffirmed by other leading seismologists of the time. However, their comments are misleading since in 1958, no instruments were available to record rotational motions. The lack of rotations was taken as a fact of life, and was left largely unexamined until the late 1990’s. Measurements in Japan and Taiwan in 1998 and 1999 found that rotations in the near-field can be 10 to 100 times greater than originally thought (Lee, et al., 2009). Since then more instruments have been installed, and more recordings have been made. The total amount of recordings is still very small, but there is enough data present to begin to try and understand rotational motions. This paper will give a brief overview of rotational ground motions in relation to civil engineering and in particular soil structure interaction.

Causes of Rotational Motions

Rotational ground motions are the result of a type of wave called surface waves. These waves travel much slower than body waves (such as shear and pressure waves). There are two different types of surface waves, each with their own particle motion. These waves are called Love Waves and Rayleigh Waves.

Love waves have particle motion in the horizontal perpendicular direction relative to the direction of wave propagation (shown in Figure 2). The motion is very similar to shear waves except that the amplitude of motion decreases with depth. This type of wave can create twists in the horizontal plane (x and y plane). Twists can cause many adverse effects, which will be discussed in more detail in the following sections.

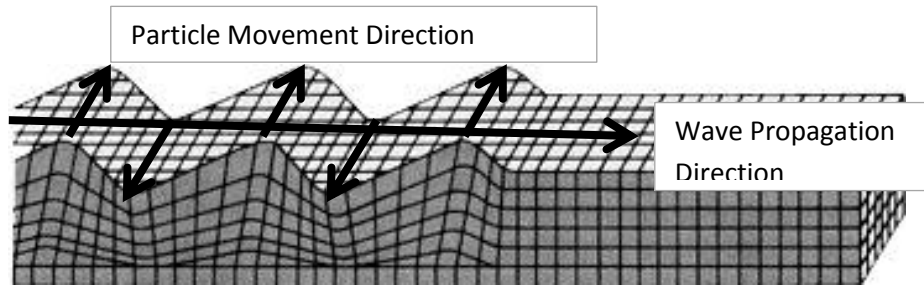


Figure 2: Love Wave (USGS, 2009)

Rayleigh waves have particle motion that is elliptical in the direction of wave propagation (shown in Figure 3). Again, the motion amplitude (size of the ellipses) decreases with depth. This type of motion creates tilting effects. Tilting can create many problems for structures, especially if the structure is very tall. Tilting can also increase or decrease rocking foundation effects, helping to keep the structure safe, or causing it to fail. These effects will be discussed in more depth in the following sections.

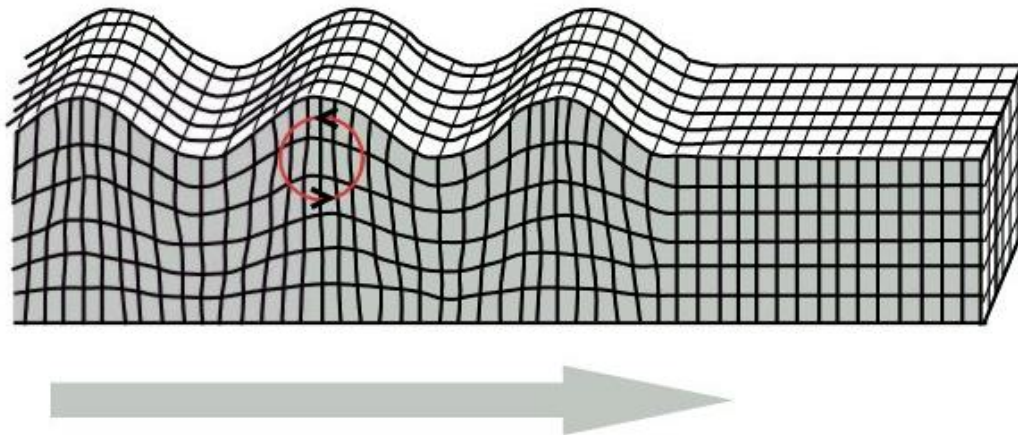


Figure 3: Rayleigh Wave (USGS, 2009)

Site and Fault Characteristics

Rotational motions vary depending on the sites soil type and location in relation to the fault. A report by Cucci & Tertulliani (2011) outlines correlations between site and source effects, and observed rotations from the 2009 M_w 6.3 L'Aquila Earthquake in Central Italy. Their findings could have significant implications for California since many conditions apply to this area.

The main correlation related the epicentral distance to rotations. Cucci & Tertulliani found that 98% of observed rotations were within one fault length and 89% were within 15 kilometers of the epicenter. This means that we would expect to see meaningful rotations only in the near field. For California, this has significant implications since the majority of our large cities are in the near field of some major faults. The San Francisco Bay Area and Los Angeles Area are both littered with faults, making all those regions subject to near field ground motions.

Another correlation they found related rotations to the soil at the site. They found that the majority of rotations occurred at sites on soft terrains such as artificial fills and alluvial deposits. Many areas in California that are in active fault zones are on these types of deposits. The San Francisco Bay Area has many areas of fill and several sections that are on alluvial deposits. The same is true for the Los Angeles Area.

One other correlation they found related directivity effects to rotations. In front of the fault propagation (SE direction), Cucci & Tertulliani found that rotations were observed up to 23 kilometers from the epicenter. On the other side of fault propagation (NW direction), they found rotations only 5 kilometers from the epicenter. This can be seen in Figure 4. Many structures in California lie in the direction of possible fault propagation and could lead to much greater damage in those structures (Cucci & Tertulliani, 2011).

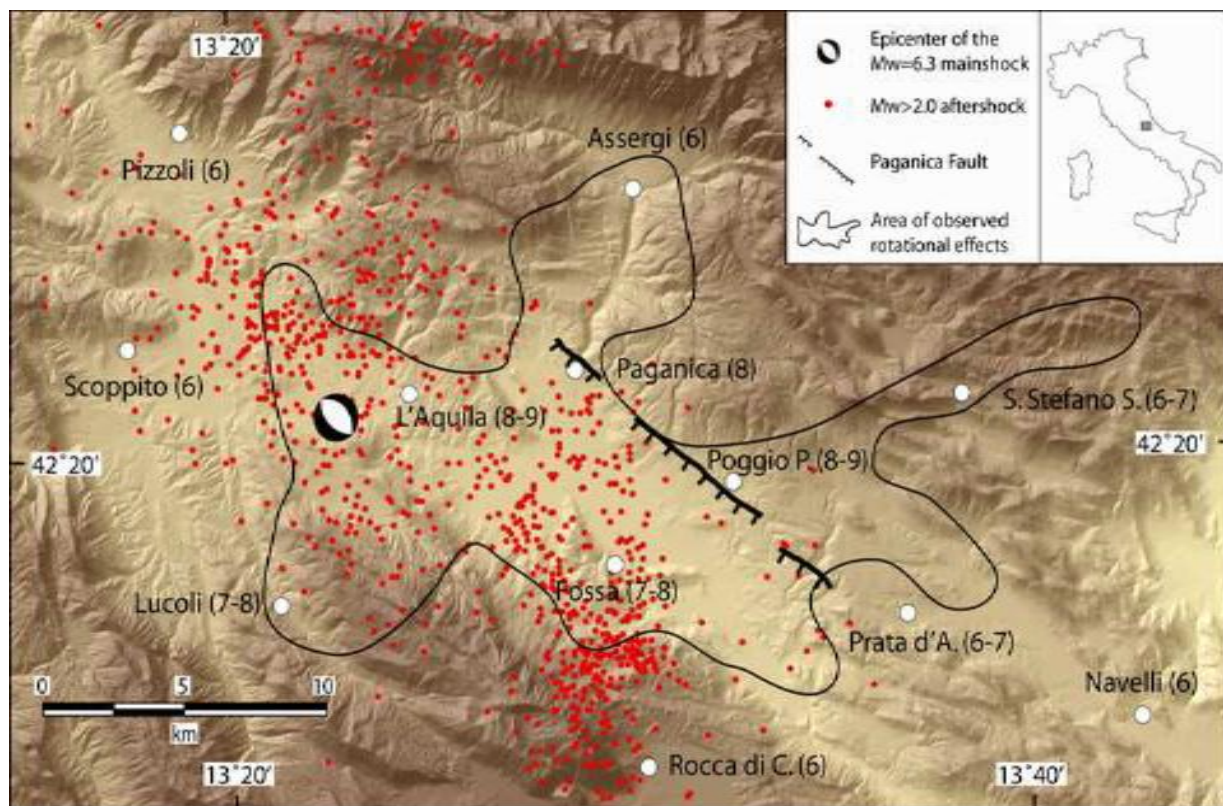


Figure 4: L'Aquila Earthquake Area (Cucci & Tertulliani, 2011)

Overall, these relations tell us where we should be looking for rotational ground motions to occur, and where it may be important to consider them for design. Many places in the United States and particularly California have all of these site characteristics at once, making them very likely to be subjected to rotational ground motions. The San Francisco Bay Area has all of these site characteristics in many places. Figure 5 shows a map of the San Francisco Bay Area with different shaking hazards

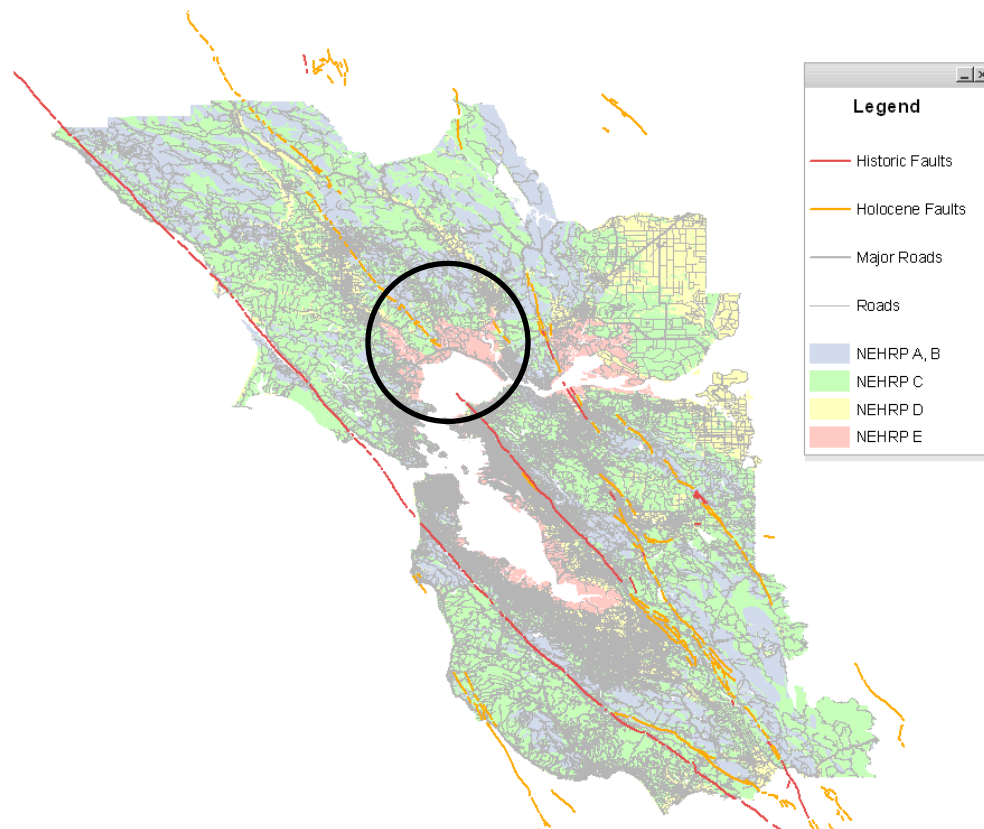


Figure 5: Soil Type and Shaking Hazard Map with Faults Marked (USGS, 2009)

represented by different colors. The areas with the worst shaking hazard (soft soils that amplify the ground motions), are in red. The shaking hazard is less as you move from red, to yellow, then green, and finally blue, where the amplification amount is very small. Faults are also shown on this map as red and yellow lines. Examining this map it can be seen that many areas lie in places where all three of the previous relationships may be valid. For example, the area circled on the map shows an area that has a very soft soil, is in a possible spot that will be subject to directivity effects (from two different faults), and is very close to both the faults. Looking at the map, you can find many other such sites as well. If the relations found by Cucci & Tertulliani are true everywhere, then we could expect high rotational ground motions in these areas.

These relations still have to yet be confirmed with other sites, but the results show possible relations between site specific conditions and the amount of rotation. Further investigation of near field

earthquake sites will help strengthen these relations. Further work in this area would be extremely beneficial to the study of rotational motions by helping us put sensors in the correct locations, and help us design structures in possible rotational motion areas to withstand these motions.

Effect of Rotations on Seismographs

When recording motions in the far-field, the effects of rotations are minor. However, when used in the near-field, seismograms can record highly contaminated values due to rotations. When tilt occurs in a traditional seismograph, the tilt will falsely raise or lower the acceleration recorded. This happens because the pendulum will swing further forward relative to its base due to the tilt. Figure 6 shows the

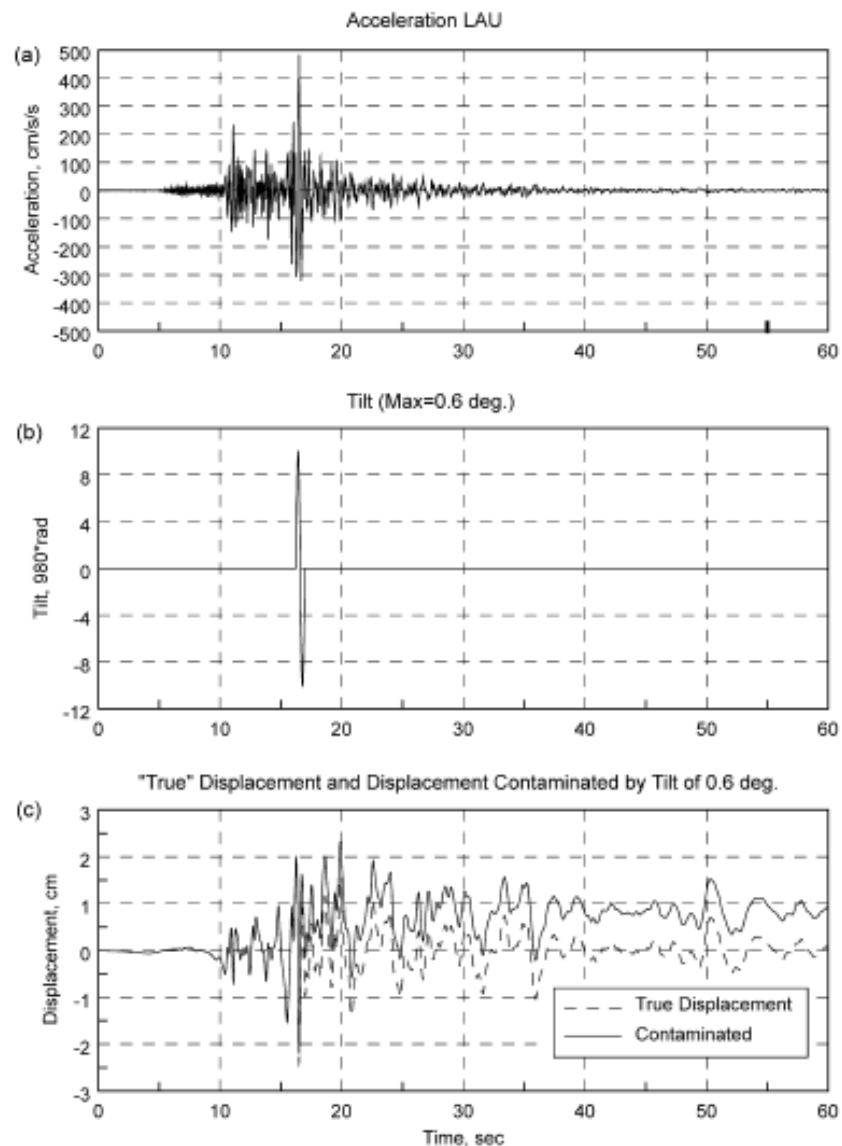


Figure 6: Contaminations of a displacement due to simple tilt (Graizer, 2005)

effects that a tilt could possibly have on the displacement calculated. The shown acceleration is from the Northridge Earthquake at Los Angeles University Hospital Grounds where a simple tilt was found to have occurred of 0.6 degrees. The original accelogram had been corrected using a method to remove the tilt. When the tilt was added back into the accelogram and then double integrated to get displacement, the displacement raised by a significant amount and a residual displacement was found.

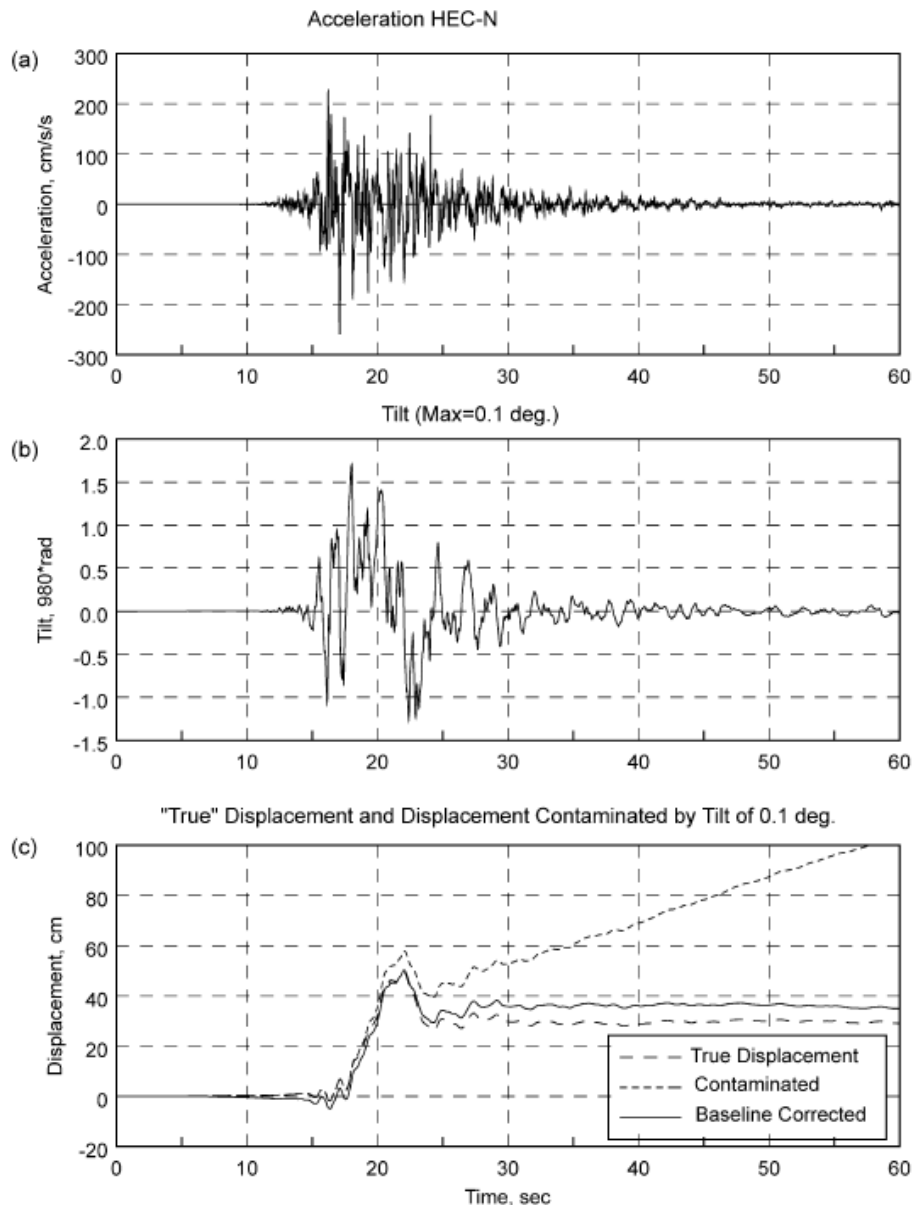


Figure 7: Comparison of "true" displacement, contaminated displacement, and corrected displacement (Graizer, 2005)

Using a method developed by Graizer, tilt can be removed from a seismogram and attempted to be corrected for. Figure 7 shows the original displacement obtained by double integrating the acceleration (line labeled "contaminated"), the "true" (determined based on other knowledge) displacement and the baseline corrected displacement from using Graizer's method. The tilt spectrum in

this graph was created assuming that the tilt spectrum is proportional to the ground velocity spectrum (discussed more later). These graphs show the effect that rotation can have on recordings and the importance they may have on structures. They also show us that current correction methods may not be adequate for translational only recordings in the near field. The graphs shown in Figure 7 were considered well processed, yet they have a significant tilt associated with them (Graizer, 2005).

Measuring Rotations

The measurement of rotations has been a slow process. Examination of classic elastic theory in the late 1970's predicted that rotations may exist at a larger scale than we originally thought. However, without the proper technology to record seismic wave rotations, it was all just theoretical. In the last decade, new instruments have been designed that allow for the measurements of rotations and today two types of measurement systems exist: the Ring Laser and the seismometer array.

The Ring Laser (**Error! Not a valid bookmark self-reference.**) uses mirrors set up in a triangle or square to measure rotations. Two laser beams are emitted, one traveling clockwise around the closed loop of square mirrors ("Ring") and the other travelling counter-clockwise. If the disc they are set up on



Figure 8: Ring Laser in Bavaria, Germany (University of Canterbury)

were to rotate clockwise, the beam traveling in the clockwise direction will take longer to reach its starting position again compared to the beam traveling in the counter-clockwise direction. The device measures the phase shift created in this process and can compute the rotation amount (University of Canterbury).

The Ring Laser has the advantage of being extremely sensitive. It can record rotations in the extremely far field (1000's of miles). However, this accuracy comes at a high cost (the pictured system cost \$19 million) and makes it difficult for

many of these to be installed, making the chances of recording a near-field earthquake very remote. However, some near field data has been recorded in Christchurch, New Zealand and a few other places around the world.

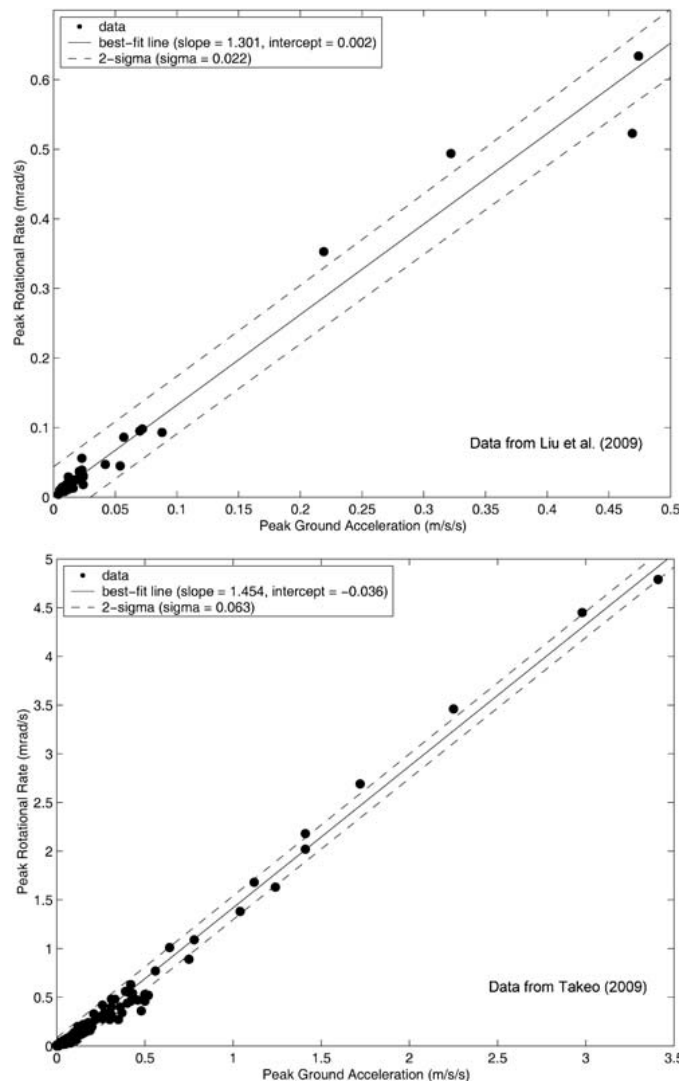
The other way to measure rotations is with seismometer arrays. These are groups of triaxial (take readings in three directions) seismometers that are installed in fairly close proximity to each other. After an earthquake, an analysis can be performed to see how the seismometers moved in relation to each other and rotations can be found. This system is much cheaper to install and requires less maintenance than the Ring Laser but has less accuracy. Despite its shortcomings, the seismometer array is the most popular to use due to its ease of use and ability to install many more around the world.

While the seismometer array is much cheaper, few are currently installed (however many have been being installed). The main locations of these arrays include Taiwan and Japan with a recent installation in southern California. Both have recorded near field earthquakes and their associated rotations.

Empirical Relationship between PRV and PGA

Even though the amount of rotational data recorded has been very small, empirical relations between the peak rotational velocity (PRV) and peak ground acceleration (PGA) seem to be very

promising. Analysis's, as shown in Figure 9, to two different sets of data by Lee et al. (2009) show that a linear relation seems to be suitable. The values for the slope of the line (b) and the intercept of the line (a) with 95% confidence intervals are shown in the table also included in Figure 9. The range and values given show us that the values are fairly similar but are not identical. However, since the data set is so small (52 samples and 216 samples) the relation cannot be determined (if any exists) at this time (Lee, et al., 2009).



| Data Set | Data Samples | $b \pm \epsilon_b$ (sec/km) | $a \pm \epsilon_a$ (mrad/sec) | ϵ (mrad/sec) | r_{xy} |
|--------------------------|--------------|-----------------------------|-------------------------------|-----------------------|----------|
| Liu <i>et al.</i> (2009) | 52 | 1.301 ± 0.028 | 0.002 ± 0.003 | 0.028 | 0.988 |
| Takeo (2009) | 216 | 1.454 ± 0.010 | -0.036 ± 0.004 | 0.060 | 0.995 |

Figure 9: Graphs of PRV versus PGA for three data sets (Lee, et al., 2009)

SDOF Equations of Motion and Response Spectra

Single-degree-of-freedom equations of motion for both translational motions only and translational with rotational motions are developed by Kalkan & Graizer (2007). These equations are summarized below.

$$m\ddot{u} + c\dot{u} + (k_0 - k_G)u = -m\ddot{u}_g \quad (\text{Translational Motion Only}) \quad (1)$$

$$m\ddot{u} + c\dot{u} + (k_0 - k_G)u = -(m\ddot{u}_g + mg\alpha + m\ddot{\alpha}l) \quad (\text{Translational Motion with Tilt}) \quad (2)$$

$$m\ddot{u} + c\dot{u} + ku = -(m\ddot{u}_g + mg\phi + mg\alpha + m\ddot{\alpha}l) \quad (\text{Translational Motion with Tilt}) \quad (3)$$

where k_0 = the initial stiffness

$$k_G = \text{Geometric Stiffness Term} = \frac{mg}{l}$$

ϕ is the angle of tilt of the equivalent fixed base system (as shown below)

All three of these equations take into account the P- Δ effect (the overturning moment due to tilt). A diagram of these systems can be seen in Figure 10 and Figure 11. It can be seen in both the figure below and the equations above that the addition of tilt on a SDOF system adds an additional lateral force. The tilting of the base also increases the P- Δ effects by increasing ϕ (Kalkan & Graizer, 2007). The effects that this has on performance will be discussed in later sections.

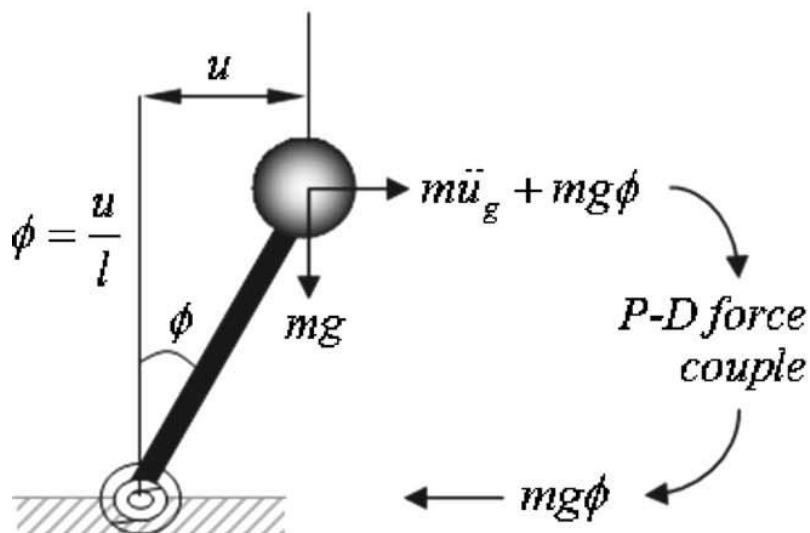


Figure 10: Translation SDOF System (Kalkan & Graizer, 2007)

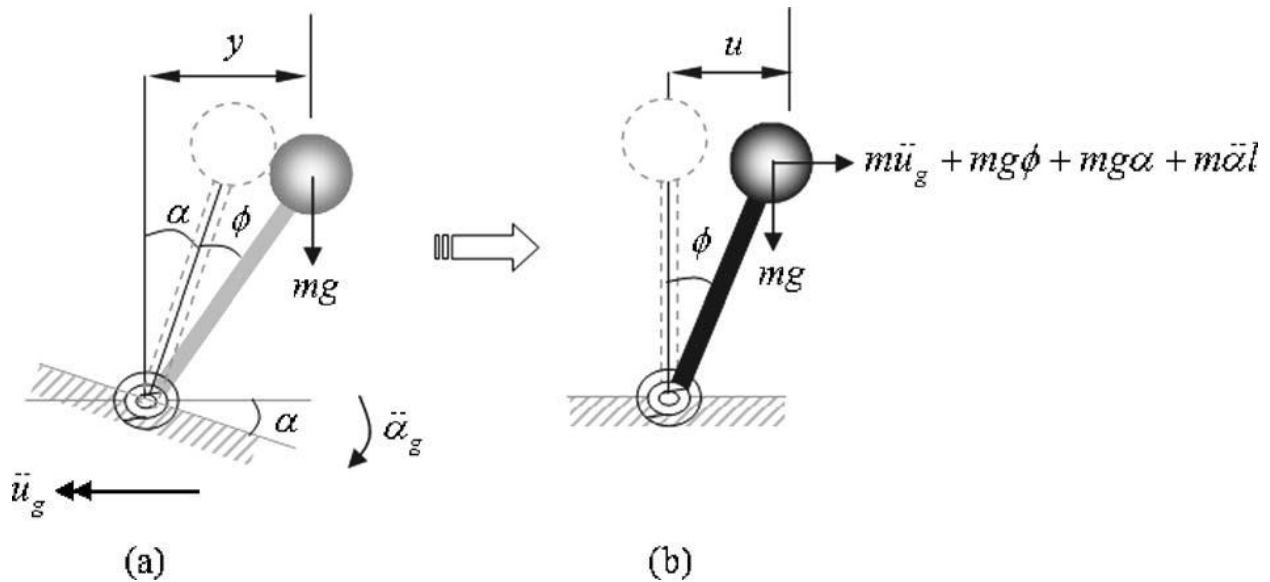


Figure 11: Translation and Rotational SDOF System (Kalkan & Graizer, 2007)

From these equations it is possible to create Response Spectra for both translational only and coupled (translational and rotational) motion. As can be seen in Figure 12, the coupled motion

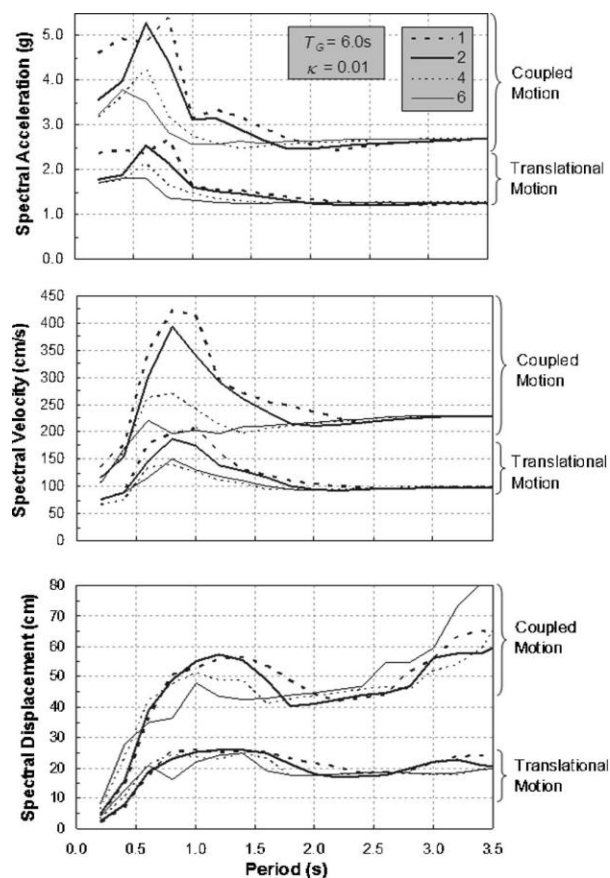


Figure 12: Response Spectra for translational and coupled motion (Kalkan & Graizer, 2007)

consistently has higher values in all three spectra (acceleration, velocity, and displacement). At small periods, the displacements have very similar values. However they quickly diverge and end with the coupled motions being three times greater than the translational motions. This is because at high frequencies (low periods), the tilt of the SDOF system is minimal but at lower frequencies, the tilt becomes greater. It should also be noted that the different lines in the figures represent different ductility levels (μ). It can be seen that as μ increases from one (elastic response) to six that the differences in displacement are fairly constant for translational motion but vary noticeably for coupled motion. It can also be seen that at higher periods, the higher ductility material has a significantly higher displacement compared to the fully elastic response. This means that in structures that have more plastic deformation, the displacements will be greater for high natural period structures (Kalkan & Graizer, 2007).

Discussion of the Effects of Rotational Ground Motions

Rotational ground motion can be divided into two portions. The first type involves the tilting of the structures, which can cause extra overturning moments. The other type is a twisting action about a central axis. This can cause further stress to the system. In the case of a bridge, both of these types of motion can play a large role in the behavior of the structure.

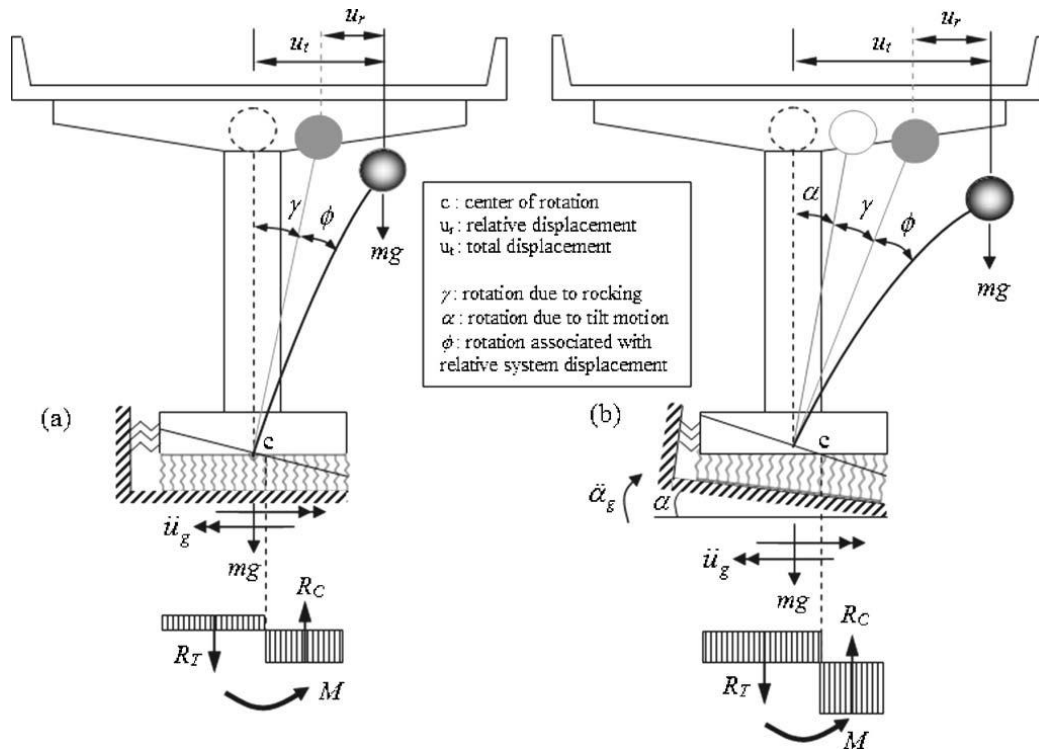


Figure 13: Rocking Motion of foundations due to translation motion (left) and coupled motion (right)

When looking at a bridge design, both the strength of the members and the reaction of the subgrade should be considered (Figure 13). In the traditional case of translational motion only, the soil provides a reactive force that dampens the overturning moment. In the figure this can be seen by R_T and R_C terms. If rotations are included, the increased moment will increase the dampening demand of the soil, as can be seen in Figure 13. If the foundation is extremely rigid, then this increased moment will not translate to the soil, but instead increase shear stresses at the base. This increase could cause the base to fail, as was seen in the 1995 Kobe Earthquake in Japan (Figure 14). Even if the structure does not completely fail, the extra moment may cause permanent tilt in the structure by causing the material to yield and plastically deform.

The exact effects also depend on whether the natural rocking of a bridge like structure is in sync with tilt effects or out of sync. If the rocking motion is out of sync with the tilting motion of the soil, then the ground tilt will help stabilize the structure (and reduce the overturning moment). However, if the rocking moment is out of sync then the tilting ground motion will make the problem much worse (Kalkan & Graizer, 2007).



Figure 14: Base shear failure in the 1995 Kobe Earthquake

The other type of motion possible is the twisting of a structure. Again, if the foundation is very rigid, shear strains will increase in the base and possibly fail the system. A paper by Ghayamghamian, Nouri, Igel, and Tobita (2009) looked into the effects torsion has on structures. Simulations were run of buildings with different parameters subjected to torsional motions recorded at the Chiba Dense Array in Japan. They found that the addition of torsion added significant displacements for structures with translational periods of approximately 0.3 seconds. These motions were significantly underestimated from what the current code in the United States asks for (Ghayamghamian, Nouri, Igel, & Tobita, 2009). The interaction between the soil and the structure was not examined in this paper and further research would be needed to find what effect this has. Additionally, research should be done to see what effect torsion has on the displacements of bridge like structures (only square foot plans were examined in the paper above).

Further Research and Conclusions

While much more research is needed on rotational ground motions, the current studies all seem to show that rotational effects on buildings may be great. In the study by Cucci & Tertulliani, relationships between the site characteristics and amount of rotational effects were considered. They found that sites with soft soil (high amplification), in the directivity effect zone, and near the epicenter, tended to have the most number of rotations, along with the most damage. Relating this to the linear

relationship between PRV and PGA, we can see further evidence that rotational motions are highly related to damage.

Looking at the SDOF equations and response spectra's developed by Kalkan & Graizer it can be seen in a more theoretical way that rotations could have a large effect on the displacement of structures. The response spectra for displacements show that when rotations are included, the displacements of SDOF systems increase noticeably. The effects are not just limited to the tipping or twisting of structures. This effect was also seen for twisting motion by Ghayamghamian, Nouri, Igel, and Tobita, who found that twisting also increased the displacement of structures. The tipping motion also has many different soil-structure interactions such as influencing the behavior of rocking foundations. Add this to the tilting and twisting of the structures themselves and a large difference may be seen between translational motion and coupled motion.

In summary, more research is needed into the effects that rotational ground motions have on structures and their interactions with the soil. As has been shown, the possible effects of rotational ground motions are great. There is evidence that damage has occurred to buildings around the world due to rotations (Ghayamghamian, Nouri, Igel, & Tobita, 2009). However, this cannot be confirmed because the effects of rotational ground motions are not well understood. Further research will help illuminate any problems with current design specifications and help make our structures safer.

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